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EXTENSION OF THE ANALYTICAL APPROXIMATION TO
THE TRANSMISSION OF SOUND IN SHALLOW WATER
USING THE IMAGE MODEL

by

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September, 1992

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Analytical Approximation to the Transmission
of Sound in Shallow Water for Cross-Slope Propagation

by

Debra M. Livingood
Lieutenant, United States Navy
B.S., U.S. Naval Academy, 1986

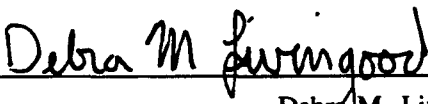
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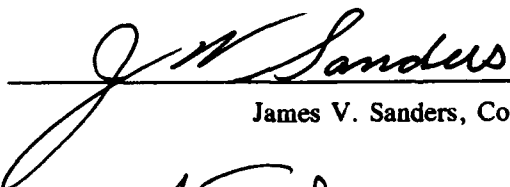
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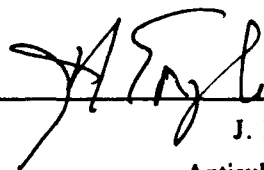
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ABSTRACT

An analytical approximation to the image theory model is developed for predicting the acoustical pressure field in a wedge-shaped ocean. This thesis is a continuation of the ongoing development of this model. Previously, limitations has restricted the source and receiver to be placed in only an upslope/downslope configuration. This thesis removes these limitations and allows the source and the receiver to be placed in cross-slope configurations.

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I. INTRODUCTION

Current historical events have necessitated a change from studying the propagation of sound in deep water to studying the propagation of sound in shallow water. With the fall of the Soviet Union and the rise of Mid-Eastern countries, Antisubmarine Warfare (ASW) is more and more likely to occur in shallow water. Shallow water provides a much more complex environment for ASW prosecution, and, unfortunately, has not had as much research as in deep water.

Image theory is one method that is being developed to predict sound propagation in shallow water. This method is more accurate than ray tracing methods because it is not limited to high frequencies. A number of theses conducted at the Naval Post Graduate School were involved with applying image theory to a wedge-shaped, shallow-water ocean. The first thesis provided the groundwork for the initial development of the image theory. The most recent [Nassopoulos, 1990] derives a simplification involving a doublet approximation and incorporates all of this information into one manageable computer program [Nassopoulos, 1992].

This thesis assimilates a more complicated cross-slope approximation into the doublet analysis which allows the source and receiver to be placed anywhere in the wedge. A

computer program has also been developed to show that the approximations are correct within the set of assumptions.

II. BACKGROUND

Research on the prediction of sound propagation in a wedge-shaped ocean has been directed in three major areas: the parabolic equation approximation, the adiabatic normal mode theory, and the image theory.

The parabolic equation can be used as a range dependent underwater acoustic propagation model. It basically replaces the Helmholtz equation with a one-way parabolic approximation which will generate the acoustic field as an initial value problem. The original version of the parabolic equation, developed in 1977 by Tappert, contained restrictions on the maximum elevation angle at the source. These limitations were reduced by Claerbout and Green and finally eliminated with the use of a higher order parabolic equation [Collins, 1987]. Because the parabolic equation is cylindrically symmetric, sloping bottoms cause a problem. One attempt to solve this problem has been attempted by sectioning off the bottom into a series of range-independent regions and then applying the normal parabolic approximation to each section [Lee et al, 1983]. Although this method increases the accuracy, it still does not alleviate the problem completely. A more recent approach to this problem has been attempted by using a rotated parabolic equation [Collins, 1990] which shows good results.

Normal mode theory is a range-independent approach. This approach has been used for open ocean predictions, but for a wedge shaped ocean, a range dependent approach is needed. For this type of approach it was shown [Pierce, 1965] that an approximation to the normal mode theory can be utilized by performing an adiabatic separation of the depth and range coordinates in the wave equation. This approach has been applied to the wedge-shaped ocean [Graves et al, 1975] but was limited to only small slopes and non-penetrable bottoms. An exact solution for the ideal wedge, where boundaries are perfectly reflected, was developed. [Buckingham, 1987] A continuing problem for adiabatic mode theory is that it can not explain the transition from the guided mode to the evanescent modes at cutoff [Jensen et al, 1980]. One hybrid approach that has been pursued to account for this is the use of the parabolic equation [Pierce, 1982] which is solved asymptotically subject to adiabatic mode initial conditions. Another method is based on tracking of local plane-wave spectra [Arnold et al, 1984] which produce intrinsic mode fields. Another method uses spectral representation based on the theory of characteristic Green's functions [Kamel et al, 1983].

Another approach in solving the wedge-shaped ocean problem is image theory. This theory predicts the pressure field from a series of projected images [Coppens et al, 1980]. A further description of this approach will be provided in the following

chapters. The basic geometry and mathematical analysis has been developed and compared to the parabolic equation model with favorable results. The upslope/downslope case has been approximated [Nassopoulos, 1992] by use of Taylor Series approximations resulting in a substantial savings in computer computational time. Although less research time has been placed into the image theory approach, it shows high potential as a viable way to predict acoustic pressure fields in a wedge shaped ocean.

III. DEVELOPMENT

The basic goal of this research is to approximate the images by a sum of doublets. Although a full description of the theories will not be incorporated into this thesis, the following can be used as a general overview.

A. IMAGE THEORY

Image theory stems from the idea that if a source is radiating near a surface, then an image, out of phase with the source and an equal distance away from the surface, is produced. In an isospeed wedge-shaped ocean, numerous images are produced [MacPherson et al, 1966]. These images form a circular pattern around the point where the surface meets the bottom and interact with a series of images each possessing an image of the surface and bottom of the wedge. The images are numbered sequentially around the upper half of the circle starting with 1 for the source, 2 for the image and so on around the circle. The lower half of the circle is labeled in a similar fashion. The pattern for the sign convention along with the numbering of the images is shown in Fig. 1.

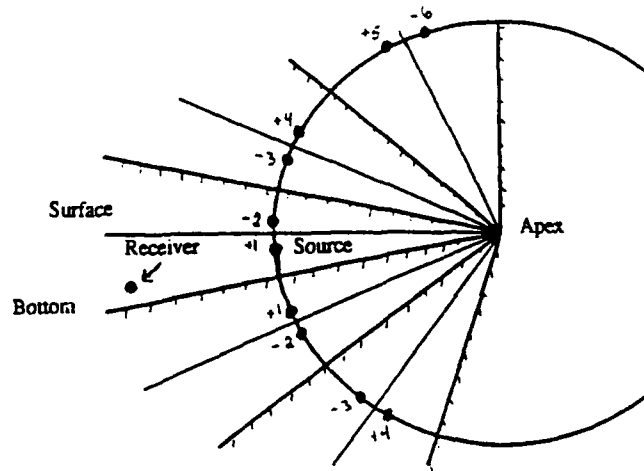
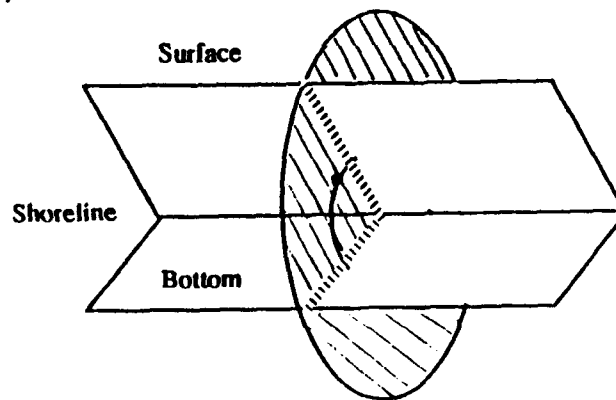


Image Pattern for a Wedge-Shaped Ocean
Figure 1

Each image contributes to the total pressure field at a point in the wedge. For each image, the distance to the receiver and the total reflection coefficient, which is the product of all the reflection coefficients along the path from the image to the receiver, can be determined. The total pressure is the sum of the pressures from all of the images. A simplified three dimensional view at Fig. 1 shows that the shoreline acts as the perpendicular axis to the circle of images. See Fig.

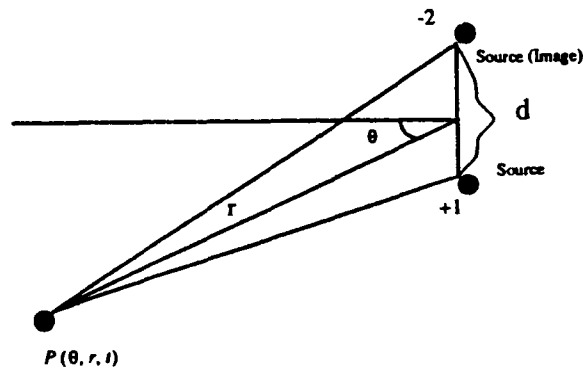
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3-Dimensional View of Wedge
Figure 2

B. DOUBLET RADIATION

The images on each side of the pressure release surface can be grouped together in pairs to form acoustic doublets: Images 1 and 2 form a doublet, 3 and 4 form another doublet, and so on around the upper and lower half of the circle. Each doublet consists of two simple sources, vibrating at the same frequency but 180 degrees out of phase. See Fig. 3.



Geometrical Presentation of Doublet
Figure 3

It can be shown that in the far field the pressure field resulting from this doublet using a far field approximation is

$$P(r, \theta, t) = j \frac{2A}{r} \sin\left(\frac{1}{2} k_1 d \sin \theta\right) e^{j(\omega t - kr)} \quad (1)$$

Where d is the separation of the source and image in the doublet, r is the distance from the field point to the

midpoint of the doublet, and θ is the angle formed by r and a perpendicular bisector of the doublet. It should be noted that, if the polarities were switched, the pressure field would change sign.

To incorporate doublets into the wedge problem, Eq. 1 needs to be modified to include the reflection coefficients. Nassapolous developed the following equation for pressure

$$P(r, \theta, t) = \frac{A}{r} [(\chi - \psi) \cos\left(\frac{1}{2} k_1 d \sin \theta\right) + j(\chi + \psi) \sin\left(\frac{1}{2} k_1 d \sin \theta\right)] e^{j(\omega t - kr)} \quad (2)$$

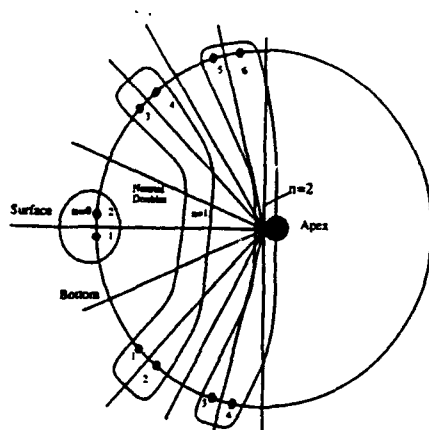
Where χ and ψ are the cumulative reflection coefficients for the negative and positive images respectively.

C. DOUBLET ANALYSIS OF THE IMAGE THEORY

1. General Description:

The purpose of this thesis is to extend Nassapolous' doublet approximation to the image theory model to incorporate cross-slope propagation. The basic assumptions remain the same: the sound speeds and densities are constant in both the wedge and the bottom, the water-air boundary is a pressure-release surface, and the slope is constant and shallow [Nassapolous, 1992]. Nassapolous developed the case for upslope and downslope propagation. Figure 4 shows how doublets are grouped together: The third and fourth upper images are grouped together with the first and second lower images ($n=1$), the fifth and sixth upper images are grouped

together with the third and fourth lower images ($n=2$) and so on around the circle until all the doublets are paired.



Representation of the Groupings of Acoustical Doublets
Figure 4

The source and image for the first surface reflected path form the neutral doublet ($n=0$) and is an exception to this grouping rule. Similar to doublet radiation, where each doublet contributes to the pressure field, now, each pair of doublets is considered the basic contributor to the total pressure field. The number of paired doublets used in this total pressure calculation can be determined by

$$N = \frac{\left(\frac{360}{\beta}\right) - 2}{4} \quad (3)$$

β is the angle between the surface and the bottom. To ensure that the pressure field is accurate, a wedge angle should be chosen such that all of the images are grouped into pairs of doublets. To insure that there is closure for the set of

images, $360/\beta$ must be a multiple of four. In calculating the total pressure field, the pressure from the neutral doublet will first be developed, followed by the pressure field from each of the paired doublets.

All distances used are scaled according to $R_{\text{scaled}} = R_{\text{real}}/X$. Two bottom types are examined in this research, a fast bottom and a slow bottom. For a fast bottom, the scaling distance X_c occurs where the lowest mode attains cut off. For a slow bottom, the lowest mode does not attain cut off, but a scaling distance X_s is used for convenience in calculations. The definitions of these scaling distances are

Fast bottom:

$$\begin{aligned} K_1 X_c &= \frac{\pi}{2 \sin \theta_c \tan \beta} \\ K_2 X_c &= \frac{\pi}{2 \tan \theta_c \tan \beta} \\ \cos \theta_c &= \frac{C_1}{C_2} \end{aligned} \quad (4)$$

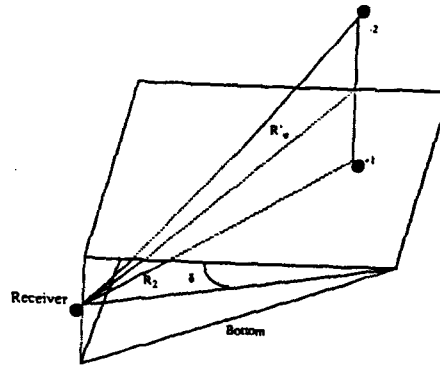
Slow bottom:

$$\begin{aligned} K_1 X_s &= \frac{\pi}{2 \tan \theta_s \tan \beta} \\ K_2 X_s &= \frac{\pi}{2 \sin \theta_s \tan \beta} \\ \cos \theta_s &= \frac{C_2}{C_1} \end{aligned} \quad (5)$$

β is the wedge angle, the subscript 1 refers to the fluid in the water, and the subscript 2 refers to the bottom [Nassopoulos, 1992].

2. Neutral Doublet ($n=0$)

The neutral doublet, as stated above, comprises of the source and upper image. The pressure field from the neutral doublet crosses no bottom boundaries therefore, no reflection coefficients need to be considered. See Fig. 5.



Geometrical Representation of Neutral Doublet
Figure 5

d is the distance between image 1 (the source) and image 2, δ is the angle formed between the surface and the plane containing the receiver and the shoreline, and R_2 is the perpendicular distance from the shoreline to the receiver. Taking Eq. 1, that was developed for doublet radiation without reflection coefficients, and applying it to the new cross slope geometry gives

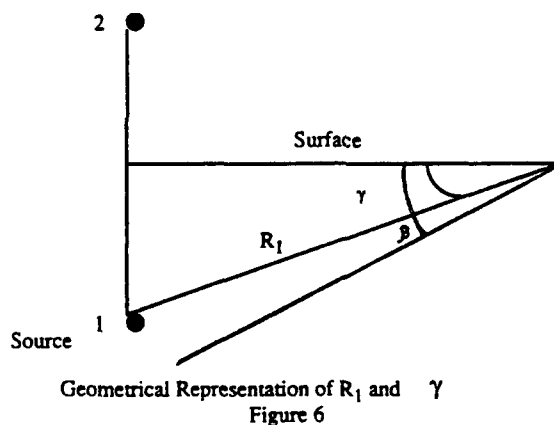
$$P_o' = j \frac{2A}{R_o'} \sin\left(\frac{1}{2} k_1 d \sin \sigma_o'\right) e^{j(\omega t - k_1 R_o')} \quad (6)$$

where P'_0 is the pressure field from the neutral doublet, R'_0 is the distance between the receiver and the midpoint between the neutral doublet and σ'_0 is the angle formed between R'_0 and the surface.

To reduce Eq. 6, the following substitution is made:

$$\frac{d}{2} = R_1 \sin \gamma \quad (7)$$

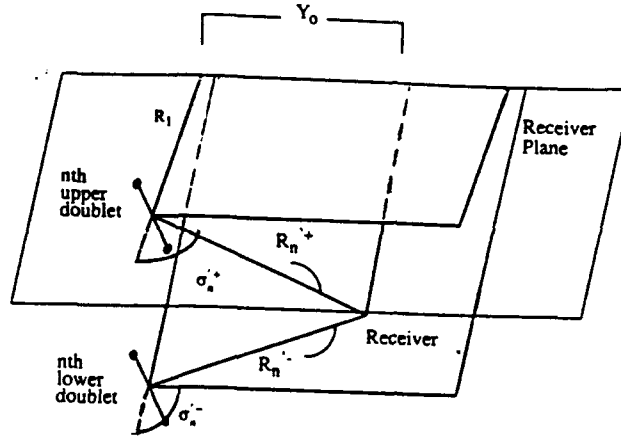
γ is the angle formed between the surface plane and the plane containing the source and shoreline, and R_1 is the perpendicular distance from the shoreline to the source. See Fig. 6.



Since δ is assumed to be a small angle, $\sin \gamma$ can be approximated by γ which reduces Eq. 6 to

$$P'_0 = j \frac{2A}{R'_0} \sin(k_1 R_1 \gamma \sin \sigma'_0) e^{j(\omega t - k R'_0)} \quad (8)$$

A further substitution can be made by applying the geometry in Fig. 7.



Geometry of Upper and Lower Doublets
Figure 8

The pressure from the upper doublet is

$$P_n^{/+} = (-1)^n j \frac{2A}{R_n^{/+}} \sin\left(\frac{1}{2} k_1 d \sin \sigma_n^{/+}\right) e^{j(\omega t - k R_n^{/+})} \quad (10)$$

and the pressure from the lower doublet is

$$P_n^{/-} = -(-1)^n j \frac{2A}{R_n^{/-}} \sin\left(\frac{1}{2} k_1 d \sin \sigma_n^{/-}\right) e^{j(\omega t - k R_n^{/-})} \quad (11)$$

The (-1) and the $-(-1)$ account for the different orientations of the top and bottom doublets.

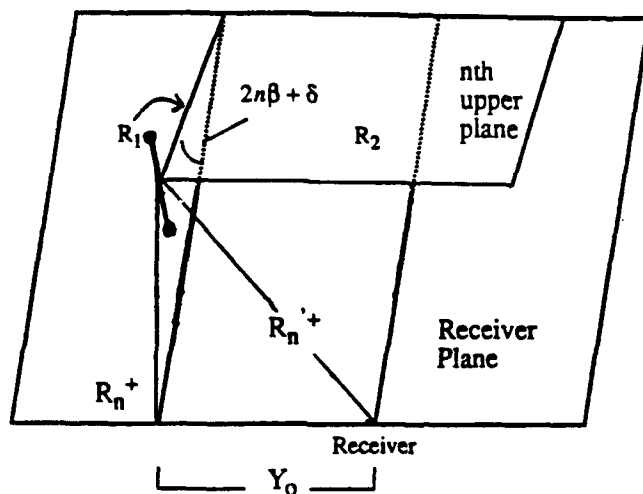
The total pressure from all of the paired doublets is

$$P_T' = P_o' + \sum_{n=1}^N P_n^{/+} + P_n^{/-} \quad (12)$$

This pressure could be calculated by a computer program, but it would take a relatively long time to compute. To shorten the computational time, and also research for an analytical approximation a Taylor series expansion is used for $R_n^{/+}$, $R_n^{/-}$, $\sin \sigma_n^{/+}$, and $\sin \sigma_n^{/-}$.

a. Derivation $R_n^{'+}$ and $R_n^{'-}$

The geometry for an upper doublet image is shown in Fig. 9.



Geometrical Representation of Upper Doublet
From this geometry Figure 9

$$(R_n^{'+})^2 = (R_n^+)^2 + (Y_0)^2 \quad (13)$$

and

$$(R_n^+)^2 = R_1^2 + R_2^2 - 2R_1R_2 \cos(2n\beta + \delta) \quad (14)$$

therefore by direct substitution

$$R_n^{'+} = \sqrt{R_1^2 + R_2^2 + Y_0^2 - 2R_1R_2 \cos(2n\beta + \delta)} \quad (15)$$

By the same reasoning, for the lower doublet

$$R_n'^- = \sqrt{R_1'^2 + R_2'^2 + Y_o'^2 - 2R_1R_2\cos(2n\beta - \delta)} \quad (16)$$

Setting Y_o to zero, Eq. 15 and Eq. 16 reduce to

$$R_n'^+ = \sqrt{R_1'^2 + R_2'^2 - 2R_1R_2\cos(2n\beta + \delta)} \quad (17)$$

$$R_n'^- = \sqrt{R_1'^2 + R_2'^2 - 2R_1R_2\cos(2n\beta - \delta)} \quad (18)$$

which match the equations developed by Nassapolous.

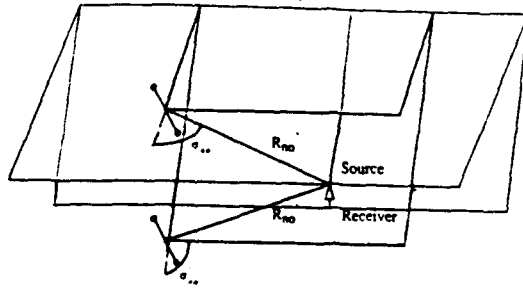
(1) *The Taylor Series Expansion for $R_n'^+$ and $R_n'^-$.*

Because $R_n'^+$ and $R_n'^-$ appears in the phase a third order Taylor series expansion is needed. Taking this expansion around $\delta=0$ gives

$$R_n' = R_{no}' + \delta \frac{dR_n'}{d\delta} \Big|_{\delta=0} + \frac{1}{2} \delta^2 \frac{d^2 R_n'}{d\delta^2} \Big|_{\delta=0} + \frac{1}{3!} \delta^3 \frac{d^3 R_n'}{d\delta^3} \Big|_{\delta=0} \quad (19)$$

This formula is the general case for both the upper and lower doublet. To get the correct formula, R_n' would be replaced with $R_n'^+$ or $R_n'^-$ as needed. R_{no}' is the distance to the nth doublet if the receiver were moved vertically to the surface. See Fig. 10. Since the geometry is now symmetrical

$$R_{no}'^+ = R_{no}'^- = R_{no}' = \sqrt{R_1'^2 + R_2'^2 + Y_o'^2 - 2R_1R_2\cos(2n\beta)} \quad (20)$$



Geometrical Representation of σ_{n0} and R_{n0}
Figure 10

Taking the first derivative yields

$$\frac{dR_n'^+}{d\delta} = \frac{R_1 R_2 \sin(2n\beta + \delta)}{R_n'^+} \quad (21)$$

$$\frac{dR_n'^-}{d\delta} = \frac{-R_1 R_2 \sin(2n\beta - \delta)}{R_n'^-} \quad (22)$$

$$\left. \frac{dR_n'^+}{d\delta} \right|_{\delta=0} = \frac{R_1 R_2 \sin(2n\beta)}{R_{n0}'} \quad (23)$$

$$\left. \frac{dR_n'^-}{d\delta} \right|_{\delta=0} = \frac{-R_1 R_2 \sin(2n\beta)}{R_{n0}'} \quad (24)$$

Taking the second derivative yields

$$\frac{d^2 R_n'^+}{d\delta^2} = \frac{[R_n'^+ R_1 R_2 \cos(2n\beta + \delta)]}{R_n'^{+2}} - \frac{[R_1 R_2 \sin(2n\beta + \delta) R_1 R_2 \sin(2n\beta + \delta)]}{(R_n'^+)^3} \quad (25)$$

$$\frac{d^2 R_n'^+}{d\delta^2} \Big|_{\delta=0} = \frac{R_1 R_2 \cos(2n\beta)}{R_{no}'} - \frac{R_1^2 R_2^2 \sin^2(2n\beta)}{R_{no}'^3} \quad (26)$$

$$\frac{d^2 R_n'^-}{d\delta^2} \Big|_{\delta=0} = \frac{R_1 R_2}{R_{no}'} [\cos(2n\beta) - \frac{R_1 R_2 \sin^2(2n\beta)}{R_{no}'^2}] \quad (27)$$

Through cancellations of the minus signs, the second derivative for the lower doublet is the same, so

$$\frac{d^2 R_n'^+}{d\delta^2} \Big|_{\delta=0} = \frac{d^2 R_n'^-}{d\delta^2} \Big|_{\delta=0} \quad (28)$$

Taking the third derivative and evaluating at $\delta=0$ yields

$$\frac{d^3 R_n'^+}{d\delta^3} \Big|_{\delta=0} = \frac{R_1 R_2}{R_{no}'} \left[\frac{-3R_1 R_2 \cos(2n\beta) \sin(2n\beta)}{R_{no}'^2} - \sin(2n\beta) + \frac{3R_1^2 R_2^2 \sin^3(2n\beta)}{R_{no}'^4} \right] \quad (29)$$

$$\frac{d^3 R_n'^-}{d\delta^3} \Big|_{\delta=0} = -\frac{R_1 R_2}{R_{no}'} \left[\frac{-3R_1 R_2 \cos(2n\beta) \sin(2n\beta)}{R_{no}'^2} - \sin(2n\beta) + \frac{3R_1^2 R_2^2 \sin^3(2n\beta)}{R_{no}'^4} \right] \quad (30)$$

Combining these pieces together, the third order Taylor series expansion is obtained

$$\begin{aligned}
R_n' &= R_{no}' \pm \delta \frac{R_1 R_2 \sin(2n\beta)}{R_{no}'} + \frac{1}{2} \frac{R_1 R_2}{R_{no}'} \delta^2 [\cos(2n\beta) \\
&- \frac{R_1 R_2 \sin^2(2n\beta)}{R_{no}'^2}] \pm \frac{1}{6} \frac{R_1 R_2}{R_{no}'} \delta^3 \left[\frac{-3R_1 R_2 \cos(2n\beta) \sin(2n\beta)}{R_{no}'^2} \right. \\
&\quad \left. - \sin(2n\beta) + \frac{3R_1^2 R_2^2 \sin^3(2n\beta)}{R_{no}'^4} \right] \quad (31)
\end{aligned}$$

(2) Phase Approximation. $R_n'^+$ and $R_n'^-$ play significant roles in the phase. Placing these terms in the phase in the third order Taylor series expansion and rearranging the terms gives

$$\begin{aligned}
\exp(j\omega t) \exp \left\{ (-jk) \left[(R_{no}') \pm \delta \frac{R_1 R_2 \sin(2n\beta)}{R_{no}'} + \frac{R_1 R_2}{2R_{no}'} \delta^2 \cos(2n\beta) \right. \right. \\
- \frac{R_1 R_2 \sin^2(2n\beta)}{R_{no}'^2} \pm \frac{R_1 R_2}{6R_{no}'} \delta^3 \frac{-3R_1 R_2 \cos(2n\beta) \sin(2n\beta)}{R_{no}'^2} \\
\left. \left. - \sin(2n\beta) + \frac{3R_1^2 R_2^2 \sin^3(2n\beta)}{R_{no}'^4} \right] \right\} \quad (32)
\end{aligned}$$

Since $e^{j\omega t}$ does not contain the index n , it can be set aside for the moment and the second term will be examined for possible reductions. In order for a term to be considered negligible, a phase error of less than $\pi/4$ is assumed. Certain assumptions also need to be made in order to represent a typical ocean environment. First, it is assumed that

$$\left| \frac{C_1 - C_2}{C_1} \right| \leq 0.1 \quad (33)$$

which is equivalent to

$$\sin\theta_c \leq 0.4 \quad (34)$$

Where c_1 is the speed of sound in the water, c_2 is the speed of sound in the bottom, and θ_c is the critical angle.

Second,

$$\beta \leq 0.1 \quad (35)$$

Finally,

$$\frac{R_1}{R'_{no}} \leq \frac{1}{10} \quad (36)$$

Whose implementation will be seen in the following analysis.

Grouping the terms inside the brackets from Eq. 32 in terms of powers in R_1 and R_2 gives

$$k \frac{R_1^3 R_2^3}{R_{no}'^5} \left[\frac{1}{2} \sin^3(2n\beta) \delta^3 \right] \quad (37)$$

$$k \frac{R_1^2 R_2^2}{R_{no}'^3} \left[\frac{1}{2} \sin^2(2n\beta) \delta^2 - \frac{1}{2} \cos(2n\beta) \sin(2n\beta) \delta^3 \right] \quad (38)$$

$$k \frac{R_1 R_2}{R_{no}'} \left[\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2 - \frac{1}{6} \sin(2n\beta) \delta^3 \right] \quad (39)$$

$$k R_{no}' \quad (40)$$

Each group needs to be compared to $\pi/4$ to determine if it can be considered negligible. Beginning with expression 37 the following inequality is set up

$$k \frac{R_1^3 R_2^3}{R_{no}'^5} \left[\frac{1}{2} \sin^3(2n\beta) \delta^3 \right] < \pi/4 \quad (41)$$

Rearranging gives

$$k \left(\frac{R_1}{R_{no}'} \right)^3 \left(\frac{R_2}{R_{no}'} \right)^2 R_2 \left[\frac{1}{2} \sin^3(2n\beta) \delta^3 \right] < \pi/4 \quad (42)$$

Making the definitions $S = R_1/R_{no}'$ and $\sin\Omega = R_2/R_{no}'$ and multiplying through by X/X gives

$$kX S^3 \sin^2\Omega \frac{R_2}{X} \left[\frac{1}{2} \sin^3(2n\beta) \delta^3 \right] < \pi/4 \quad (43)$$

where $kX = \pi / (2 \sin\theta_c \tan\beta)$ for a fast bottom.

To ensure that the left hand side of the equation is always

$\ll \pi/4$ the maximum of all powers of sine and cosine terms will be taken to be unity, with the exception of $\sin\theta_c$ which, as stated in the above assumptions, already has a maximum value of 0.4. Substituting these maximum values into Eq. 43 and rearranging gives

$$\frac{\pi}{.4 \tan \beta} S^3 \frac{R_2}{X} \leq \frac{\pi}{\delta^3} \quad (44)$$

Since β is small, $\tan \beta = \beta$ while δ , the receiver angle, falls between 0 and β . The right hand side is minimized by setting $\beta = \delta$. Making this substitution into Eq. 44 and allowing β to take on a minimum value of 0.1, reduces Eq. 44 to

$$S^3 \frac{R_2}{X} \leq 40 \quad (45)$$

Finally, substituting $S = 1/10$ according to Eq. 36 gives

$$\frac{R_2}{X} \leq 40000 \quad (46)$$

If R_2/X for some reason became larger than 40000, the term would need to be added back into the equation to keep the phase error less than $\pi/4$. Note that $\beta \geq 0.1$ is equivalent to setting a lower limit on the wedge angle of about 6 degrees. Expression 38 can be written

$$k \left(\frac{R_1}{R_{no}} \right)^2 \left(\frac{R_2}{R_{no}} \right) R_2 \left[\frac{1}{2} \sin^2(2n\beta) \delta^2 - \frac{1}{2} \cos(2n\beta) \sin(2n\beta) \delta^3 \right] < \pi/4 \quad (47)$$

Making the same substitutions as in the previous equation yields

$$\frac{\pi}{2 \sin \theta_c \tan \beta} S^2 \frac{R_2}{X} [\sin^2(2n\beta) \delta^2 - \cos(2n\beta) \sin(2n\beta) \delta^3] < \pi/2 \quad (48)$$

Once again substituting in the maximizing values gives

$$S^2 \frac{R_2}{X} < 4 \quad (49)$$

Substituting $S = 1/10$ gives

$$\frac{R_2}{X} < 400 \quad (50)$$

which allows this expression to be neglected.

Expression 39 gives

$$k \frac{R_1}{R_{no}} R_2 [\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2 - \frac{1}{6} \sin(2n\beta) \delta^3] < \frac{\pi}{4} \quad (51)$$

Making the same substitutions as in the previous equation yields

$$\frac{\pi}{2\sin\theta_c \tan\theta} S \frac{R_2}{X} [\sin(2n\beta)\delta + \frac{1}{2}\cos(2n\beta)\delta^2 - \frac{1}{6}\sin(2n\beta)\delta^3] < \frac{\pi}{4} \quad (52)$$

Rearranging the terms and substituting in the maximum values gives

$$S \frac{R_2}{X} < \frac{.02}{\sin(2n\beta)\delta + \frac{1}{2}\cos(2n\beta)\delta^2 - \frac{1}{6}\sin(2n\beta)\delta^3} \quad (53)$$

The dominate terms in the denominator are $\sin(2n\beta)\delta + 0.5\cos(2n\beta)\delta^2$. Since $1/6 \sin(2n\beta)\delta^3$ is a comparatively small number it can be neglected without increasing the phase error over $\pi/4$.

It follows that the expression for the upper doublet is

$$e^{-jk[R'_{no} + \frac{R_1 R_2}{R'_{no}} (\sin(2n\beta)\delta + \frac{1}{2}\cos(2n\beta)\delta^2)]} \quad (54)$$

and by the same method

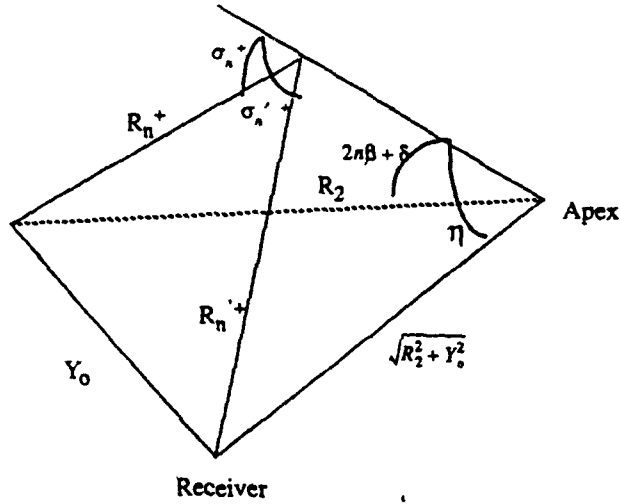
$$e^{-jk[R'_{no} - \frac{R_1 R_2}{R'_{no}} (\sin(2n\beta)\delta + \frac{1}{2}\cos(2n\beta)\delta^2)]} \quad (55)$$

for the lower doublet.

(3) *Amplitude Approximation.* It can be shown that, in the far field, the amplitude, R'_n and R'_n can be replaced by R'_{no} with a relatively small margin of error.

b. Derivation of $\sin\sigma_n'^+$ and $\sin\sigma_n'^-$

To take the Taylor series expansion of $\sin\sigma_n'^+$ and $\sin\sigma_n'^-$, an expression for each term is needed. The geometry for this is shown in Fig. 11 for an upper doublet.



Geometrical Representation of $\sigma_n'^+$ and $R_n'^+$
Figure 11

From the law of sines

$$\frac{R_n'^+}{\sin\eta} = \frac{\sqrt{R_2^2 + Y_0^2}}{\sin\sigma_n'^+} \quad (56)$$

Rearranging this gives

$$R_n'^+ \sin\sigma_n'^+ = \sin\eta \sqrt{R_2^2 + Y_0^2} \quad (57)$$

Substitution $\sqrt{1 - \cos^2 \eta}$ for $\sin \eta$ gives

$$R_n'^+ \sin\sigma_n'^+ = \sqrt{(R_2^2 + Y_0^2) - (R_2^2 + Y_0^2) \cos^2 \eta} \quad (58)$$

To get η in terms of δ a substitution for $\cos^2 \eta$ is needed. To do this the following equality is setup:

$$R_n'^{+2} = R_1^2 + R_2^2 + Y_o^2 - 2R_1R_2\cos(2n\beta + \delta) = \\ R_1^2 + R_2^2 + Y_o^2 - 2R_1\sqrt{R_2^2 + Y_o^2}\cos\eta \quad (59)$$

Canceling similar terms and solving for $\cos^2 \eta$ gives

$$\cos^2 \eta = \frac{R_2^2 \cos^2(2n\beta + \delta)}{R_2^2 + Y_o^2} \quad (60)$$

Substituting this into Eq. 58 and replacing $\cos^2(2n\beta + \delta)$ with $1 - \sin^2(2n\beta + \delta)$ gives:

$$R_n'^+ \sin \sigma_n'^+ = \sqrt{Y_o^2 + R_2^2 \sin^2(2n\beta + \delta)} \quad (61)$$

Bringing $R_n'^+$ over to the right side gives the final expression for $\sin \sigma_n'^+$.

$$\sin \sigma_n'^+ = \frac{\sqrt{Y_o^2 + R_2^2 \sin^2(2n\beta + \delta)}}{R_n'^+} \quad (62)$$

And finally, by the same reasoning the expression for $\sin \sigma_n'^-$ is

$$\sin \sigma_n'^- = \frac{\sqrt{Y_o^2 + R_2^2 \sin^2(2n\beta - \delta)}}{R_n'^-} \quad (63)$$

When the receiver is moved vertically to the surface Eq. 62 and Eq. 63 become

$$\sin \sigma_{no}' = \frac{\sqrt{Y_o^2 + R_2^2 \sin^2(2n\beta)}}{R_{no}'} \quad (64)$$

Again, by setting $Y_o=0$ for a geometrical check

$$\sin \sigma_n^+ = \frac{R_2 \sin(2n\beta + \delta)}{R_n^+} \quad (65)$$

$$\sin \sigma_n^- = \frac{R_2 \sin(2n\beta - \delta)}{R_n^-} \quad (66)$$

which agrees with the upslope/downslope case.

(1) The Taylor series expansion for $\sin \sigma_n^+$ and $\sin \sigma_n^-$. The first order Taylor series expansion taken around $\delta_0 = 0$ gives

$$\sin \sigma_n' = \sin \sigma_{n0}' + \delta \left. \frac{d \sin \sigma_n'}{d \delta} \right|_{\delta=0} \quad (67)$$

Because these terms only appear in the amplitude, the approximation $\sin \sigma_n' \approx \sin \sigma_{n0}'$ is acceptably accurate.

c. Total Pressure Including Approximations

Putting all of these equations together yields the pressure for the upper doublet,

$$P_n'^+ = (-1)^n j \frac{2A}{R_{n0}'} \left[\sin \frac{1}{2} k_1 d \sin \sigma_{n0}' \right] e^{j(\omega t)} e^{-j k_1 \left[R_{n0}' + \frac{R_1 R_2}{R_{n0}'} (\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2) \right]} \quad (68)$$

That for the lower doublet is the same except for a sign,

$$P_n' = -(-1)^n j \frac{2A}{R_{no}'} \left[\sin \frac{1}{2} k_1 d \sin \sigma_{no}' \right] e^{j(\omega t)} e^{-jk_1 \left[R_{no}' - \frac{R_1 R_2}{R_{no}'} (\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2) \right]} \quad (69)$$

The pressure from the pair is

$$(-1)^n \frac{4A}{R_{no}'} \left[\sin \frac{1}{2} k_1 d \sin \sigma_{no}' \right] e^{j(\omega t - k R_{no}')} \sin \left[\frac{k_1 R_1 R_2}{R_{no}'} (\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2) \right] \quad (70)$$

The total pressure as stated in Eq. 12 is

$$P_T' = P_o' + \sum_{n=1}^N P_n' + P_n' \quad (71)$$

Combining Eq. 9 and Eq. 70 gives the final solution for the total pressure,

$$P_T = j \frac{2A}{R_o'} \sin(\Gamma_o' \gamma \delta) e^{j(\omega t - k_1 R_o')} + \sum (-1)^n \frac{4A}{R_{no}'} \left[\sin \frac{1}{2} k_1 d \sin \sigma_{no}' \right] e^{j(\omega t - k R_{no}')} \sin \left[\frac{k_1 R_1 R_2}{R_{no}'} (\sin(2n\beta) \delta + \frac{1}{2} \cos(2n\beta) \delta^2) \right] \quad (72)$$

4. Validation

To validate the analysis of doublet cross-slope propagation, a computer program was developed. See Appendix "A". Different inputs of γ_o , R_1 , and R_2 were used along with a wedge angle and source depth of 7.5 and 3.75 degrees respectively. These inputs were also put into the program URTEXT and a comparative table was constructed. See Table 1.

TABLE 1

| COMPARISON OF DOUBLET ANALYSIS TO IMAGE THEORY | | | | | | | |
|--|--------|--------|--------|---|--------|--------|--------|
| $\beta = 7.5$ $\gamma = 3.75$ # of depth points = 6 | | | | | | | |
| R1 = 1 R2 = 15 Y0 = 0 | | | | R1 = 1 R2 = 12 Y0 = 8 | | | |
| DOUBLET | | IMAGE | | DOUBLET | | IMAGE | |
| AMP | PHS | AMP | PHS | AMP | PHS | AMP | PHS |
| .19230 | -1.189 | .19020 | -1.174 | .20760 | .97186 | .14901 | .99135 |
| .37155 | -1.192 | .36747 | -1.175 | .40214 | .97103 | .28788 | .99132 |
| .52564 | -1.195 | .51973 | -1.177 | .57139 | .96959 | .40713 | .99133 |
| .64414 | -1.199 | .63659 | -1.179 | .70471 | .96741 | .49862 | .99135 |
| .71913 | -1.203 | .71006 | -1.180 | .79371 | .96432 | .55614 | .99135 |
| .74575 | -1.207 | .73519 | -1.180 | .83276 | .96002 | .57590 | .99138 |
| $\Delta\text{AMP} = .0066$ $\Delta\text{PHS} = .01898$ | | | | $\Delta\text{AMP} = .1729$ $\Delta\text{PHS} = .0232$ | | | |
| R1 = 1 R2 = 14 Y0 = 3 | | | | R1 = 1 R2 = 8 Y0 = 9 | | | |
| DOUBLET | | IMAGE | | DOUBLET | | IMAGE | |
| AMP | PHS | AMP | PHS | AMP | PHS | AMP | PHS |
| .16437 | .77749 | .15456 | .80884 | .18308 | -.2626 | .12944 | -.2403 |
| .31909 | .77590 | .29861 | .80795 | .35338 | -.2536 | .25005 | -.2402 |
| .45507 | .77353 | .42229 | .80677 | .49899 | -.2554 | .35361 | -.2402 |
| .56437 | .77059 | .51721 | .80558 | .60956 | -.2580 | .43309 | -.2403 |
| .64061 | .76720 | .57687 | .80473 | .67701 | -.2617 | .48304 | -.2403 |
| .67940 | .76316 | .59736 | .80443 | .69602 | -.2671 | .50009 | -.2403 |
| $\Delta\text{AMP} = .0423$ $\Delta\text{PHS} = .0351$ | | | | $\Delta\text{AMP} = .1447$ $\Delta\text{PHS} = .0178$ | | | |
| R1 = 1 R2 = 13 Y0 = 6 | | | | R1 = 1 R2 = 2 Y0 = 10 | | | |
| DOUBLET | | IMAGE | | DOUBLET | | IMAGE | |
| AMP | PHS | AMP | PHS | AMP | PHS | AMP | PHS |
| .19161 | .77072 | .14813 | .74146 | .00110 | -.3287 | .00016 | -.0074 |
| .36918 | .77044 | .28616 | .74157 | .00216 | -.3376 | .00030 | -.0376 |
| .51968 | .76982 | .40469 | .74174 | .00320 | -.3477 | .00043 | -.0112 |
| .63207 | .76894 | .49564 | .74189 | .00415 | -.3607 | .00052 | -.0134 |
| .69820 | .76776 | .55281 | .74199 | .00500 | -.3813 | .00055 | -.0195 |
| .71336 | .76620 | .57226 | .74203 | .00573 | -.4041 | .00055 | -.0251 |
| $\Delta\text{AMP} = .11073$ $\Delta\text{PHS} = .0272$ | | | | $\Delta\text{AMP} = .0031$ $\Delta\text{PHS} = .3421$ | | | |

It is shown that the doublet cross-slope propagation results are in good agreement with the URTEXT results. It should be noted though, that for the results to compare favorably, the wedge angle that is chosen must ensure that the number of wedges are an even multiple of four.

IV. CONCLUSIONS AND RECOMMENDATIONS

Image theory is an excellent method for predicting the transmission of sound in shallow water. It is an important area of research because it is directly applicable to shallow water Anti-submarine Warfare. Other methods that are being examined include the Parabolic Equation approximation, ray tracing methods, and the Adiabatic Normal Mode theory. Image theory shows the most promise for predicting the acoustical pressure fields in a wedge-shaped ocean because it can predict pressure fields for cross-slope and for all frequencies. Image theory can also deal with the transitional area at cut off, a region that is difficult for normal mode theory.

Previous theses have laid the groundwork for the image theory model. This thesis has extended the doublet approximation to cross-slope propagation. The base approximation used, $R_1^2 \ll R_2^2 + Y_0^2$, limits the extension to the far-field. Another limiting restriction on this thesis basically states that for a phase error of $\pi/4$ or less, the scaled receiver distance R_2/X must be less than 400. Geometrically this says that when the receiver gets too far away the phase errors combine and the pressure equation developed in Eq. 72 is no longer valid. One further

restriction is that the wedge angle must be chosen such that the number of wedges produced is an even multiple of four. Because of this, when the dipoles are grouped into pairs of doublets, one dipole, 180 degrees from the neutral doublet, will be left ungrouped. This will only be a significant factor when the grouped dipoles cancel completely leaving only the dipole to contribute to the pressure. The effects of this dipole can also be seen in Table 1: The results vary when R_1 gets small and Y_0 gets large. Although this dipole can have noticeable effects on the pressure in the rigid bottom case, when reflection coefficients are incorporated, the effects become negligible.

The next step in this research would be to incorporate the reflection coefficients for the upper and lower doublet into Eq. 72. The reflection coefficients though, because of their large effect on the pressure, need to be calculated individually for each image. Nassopoulos incorporated the reflection coefficients into the upslope/downslope case, but an extension is still needed for the cross-slope case.

APPENDIX "A"

```

10 REM WEDGE DEBIF, DIPOLE APPROXIMATION
20 REM cross slope, wedge with rigid bottom, including third order approx
30 PI=3.14159265
40 INPUT "angles(deg) of wedge, source: B,G =",B,G
50 INPUT "M1 = B/(delta D) =",M1
60 NPTS=INT(((INT((360/B+.0001)-2)/4)+.0001)
70 INPUT "source, receiver, apex distances: R1,R2,Y0 =",R1,R2,Y0
80 INPUT "c1/c2 =",C
90 T6=180/PI: B=B/T6: G=G/T6
100 STARCOS = SQRT(ABS(C+C-1)): T4=PI/(2*STARCOS*TAN(B))
110 LPRINT USING "THESE APPROX angles: wedge= ###.# source= ###.#";B*T6,G*T6
120 LPRINT USING "distances: source=###.## receiver=###.## shore=###.#";R1,R2,Y0
130 LPRINT USING " c1/c2= ###.# ";C
140 LPRINT USING "k1v=pi/(2 tanB sgrabs(1-c^2))=###.####";T4
150 LPRINT USING "No. of Dipole-Pairs =###.##";NPTS
160 LPRINT " DEG AMP PHASE "
165 DIST=2*R1*SIN(G)
170 Y2=Y0+Y0: R22=R2*R2
180 C2=C*C: D2=Y0+Y0+R1+R1+R2+R2
190 P3=2*R1+R2
200 FOR M=1 TO 100: D=D+B/M1: IF (B-D)<-.0001 THEN 380
210 R0=SQRT(D2-R3*COS(D)): GAM0=R1*R2/R0
220 T=(2/R0)*SIN(T4+GAM0*G*0)
230 P1=T*SIN(T4+R0): P2=T*COS(T4+R0)
240 P3=0: P4=0
250 FOR N=1 TO NPTS
260 RN=SQRT(D2-R3*COS(2*N*B))
262 RN1=(T4+R1+R2*SIN(2*N*B))/RN
264 RN2=(T4+R1+R2*COS(2*N*B))/RN
270 SNS=(SQRT(Y2+R22*(SIN(2*N*B))^2))/RN
280 X=((-1)^N)*(2/RN)*SIN(.5*T4+DIST*SNS)
282 THDPOS=-T4*RN - D*RN1 - .5*D^2*RN2
283 THDNEG=-T4*RN + D*RN1 - .5*D^2*RN2
284 THDR = COS(THDPOS)-COS(THDNEG)
285 THDI = SIN(THDPOS)-SIN(THDNEG)
287 REAL1 = -X*THDI
289 IMAG1 = X*THDR
300 P3=REAL1 + P3
310 P4=IMAG1 + P4
320 NEXT N
330 PR=P1+P3: PIM=P2+P4
340 AMP=SQRT(PR*PR+PIM*PIM)
350 PHS=ATN(PIM/PR)
360 LPRINT USING " ###.## ###.#### ###.#### "; D*T6,AMP,PHS
370 NEXT M
380 END

```

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